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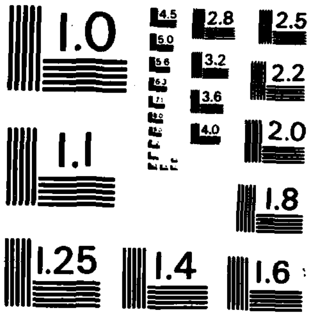


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# DEPARTMENT OF DEFENCE

## DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

## MATERIALS RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AD-A142 881

## REPORT

## MRL-R-907

# SHOCK WAVE MODELLING AND THE HULL COMPUTER CODE
# FORMATION OF MACH STEMS

J.A. Waschl





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## C O N T E N T S

# SHOCK WAVE MODELLING AND THE HULL COMPUTER CODE - FORMATION OF MACH STEMS

## 1. INTRODUCTION

Shock waves from detonating explosive charges are capable of inflicting damage over wide distances. Their formation, their propagation and their properties at any instant are of fundamental importance in assessing their effectiveness against various targets. Experimental measurements of shock parameters can be a difficult, costly and a time consuming process. Use of appropriate numerical tools is probably justified when estimates are required; confirmatory experiments can then be reduced to an absolute minimum.

This Report describes the implementation of the HULL computer code in Australia, and its initial application to the propagation of shock waves up an inclined ramp in a Shock Tube and the study of any associated Mach Stem formation and Triple Point trajectory.

## 2. HULL CODE

HULL [1] employs an Eulerian finite-difference scheme which can be applied to either two-or three-dimensional problems. It is a completely independent package made up of three main programs each capable of running separately plus two supplementary programs. These programs are:-

<u>KEEL</u> The problem is defined in KEEL. It sets up the calculation grid and stores the initial values for each cell including any special boundary conditions.

<u>HULL</u> The number-crunching is carried out in HULL. Not surprisingly, this program provides the name of the whole system. Here, the files created by KEEL are used in the finite difference scheme to advance the problem in time increments.

<u>PULL</u> This program takes the output supplied from HULL and provides the mechanism for plotting a variety of graphs, vector diagrams or histograms.

<u>PLANK</u> This supplementary program is a job monitor. It validates the input, generates the various options for the particular problem and aborts if it finds errors or inconsistencies.

POST This supplementary program provides file management for the whole operation. It examines the input data and then tailors the composition of the KEEL, HULL and PULL programs to suit.

In this way, there is no unused code incorporated into the run, thus ensuring that operating time and cost are reduced to a minimum.

Before being able to make an assessment of the potential of a code of HULL's size and sophistication, on the Cyber 7600, some modifications to the software were naturally required. These changes were successfully achieved using the sparse documentation available.

## 3. THE PHYSICAL PROBLEM

An outline of the two-dimensional cartesian problem is shown in Fig. 1. A mass of shocked air (the shock wave is non-decaying) travelling along a tube is about to impinge on a ramp angled at 27° to the horizontal. A small opening at the top allows the air flow to proceed beyond the wedge. T represents the absolute temperature, P the pressure, $\rho$ the density and u the velocity. All symbols are stated in the standard form according to Ben-Dor [2].

The aim of this work is the generation of expertise with the HULL code while considering a problem that can be examined in the shock tube at the Australian National University, Canberra. Both approaches should show and identify the Mach Stem and the Triple Point trajectory.

The problem was defined in KEEL and the data required (in cgs units) are shown in Appendix A. The more important details are discussed in the following paragraphs.

The air-filled tube is assumed to have perfectly reflecting internal walls. The equation-of-state assumes a fixed gamma law [3].

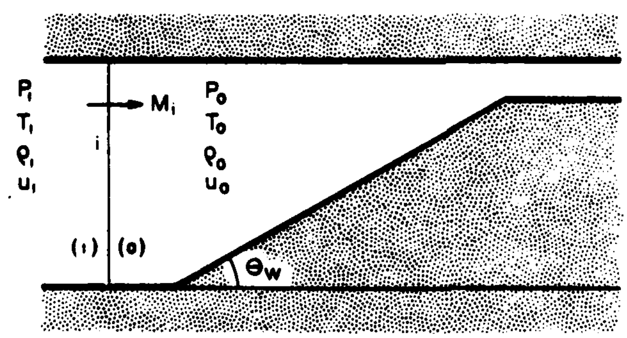


FIGURE 1. Problem Set-up

Physical parameters for the unshocked and shocked air are given in Table 1. The unshocked data are available from KEEL, while the supplied shocked-air values are assumed derived from experiment and the input wave velocity, and entered via the HULL data file as shown in Appendix B. These data will be verified later. All other parameters are evaluated within HULL.

TABLE 1.

PHYSICAL PARAMETERS OF SYSTEM

| QUANTITY | UNSHOCKED AIR | SHOCKED AIR |
|---|---|---|
| Shock wave velocity (m/s) | - | $5.00877 \times 10^2$ |
| Ratio of specific heats | 1.4003 | 1.4003 |
| Density ($kg/m^3$) | 1.225 | 2.222 |
| Particle velocity (m/s) | 0 | $2.247 \times 10^2$ |
| Specific Internal energy (J/kg) | $2.044 \times 10^5$ | $2.692 \times 10^5$ |
| Pressure (Pa) | $1.013 \times 10^5$ | $2.393 \times 10^5$ |

Within KEEL, a series of monitoring points is set up as shown schematically in Fig. 2. These selected locations are used to collect local time-varying information of interest for possible plotting. Justification for their use is described later.

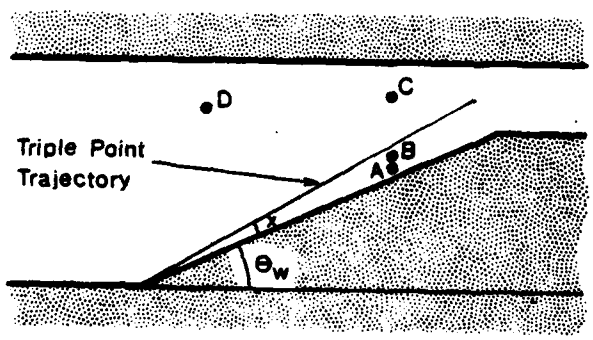


**FIGURE 2.** Schematic showing station locations.

Appendix C is an example of the input data required for plotting velocity vectors and overpressure as a function of time, at these monitoring stations, for the PULL program. Results for vector velocity, overpressure variation and pressure contours are given at various times in Figures 3,4 and 5. The times given at the bottom of each plot correspond to a time zero when the shock front is well before the beginning of the ramp.

In Figures 3(i) & (ii) the vector velocity of the flow is shown. Here the influence of the wedge on the direction of flow is apparent. Figs. 3(iii) & (iv) give the velocity vectors for these same times, but in a logarithmic scale. This can be a useful display since large changes to the flow direction become evident as can be seen, for example, in Fig. 3(iv) where the skew vectors near the front of the flow by the top boundary seem to give early indication of the influence of the reflective top boundary.

Figures 4(i) - 4(iv) show the variation of pressure as a function of time at the four locations A,B,C and D specificed in Fig. 2. These points were selected from theoretical investigations, which indicated that the triple point trajectory associated with a Mach Stem should pass between B and C. Therefore measurement of a parameter such as overpressure should provide some indication of the program's applicability.

If a Mach Stem were formed, as suggested, the overpressure plots for A and B would be significantly different from that at C as is observed. The peak $P_m$ as shown in Figs. 4(i) and 4(ii) can be attributed to a Mach Stem. In Figs. 4(iii) & 4(iv) the first peak, $P_i$, is caused by the passage of the incident shock. The second peak, $P_r$, in Fig. 4(iii) & 4(iv) is caused by the shock reflected from the surface of the wedge as it passes through the pre-shocked region around the respective points C & D on its way towards the top boundary. The time interval between the arrival times of the peaks $P_i$ and $P_r$ for locations C and D and the change in magnitude for $P_r$ can be attributed to the longer path length, and therefore longer travelling time and greater divergence experienced by the reflected wave arriving at location D.

All subsequent peaks in Figs. 4(i) - 4(iv) are caused by repeated reflections between the wedge and top boundary and are of no relevance to this discussion. Table 2 lists the values of the overpressures $P_i$, $P_r$ and $P_m$ at all four locations.

Figs. 5(i)-(iii) show typical contour pressure plots obtained at the indicated times. It would appear from these plots that a classical Mach Reflection has been found. The incident and reflected waves are well defined as is the formation of the Mach Stem with associated triple point. Using these plots the position of the triple point was estimated and the trajectory found to have an angle of 8.2° ± 0.8°.

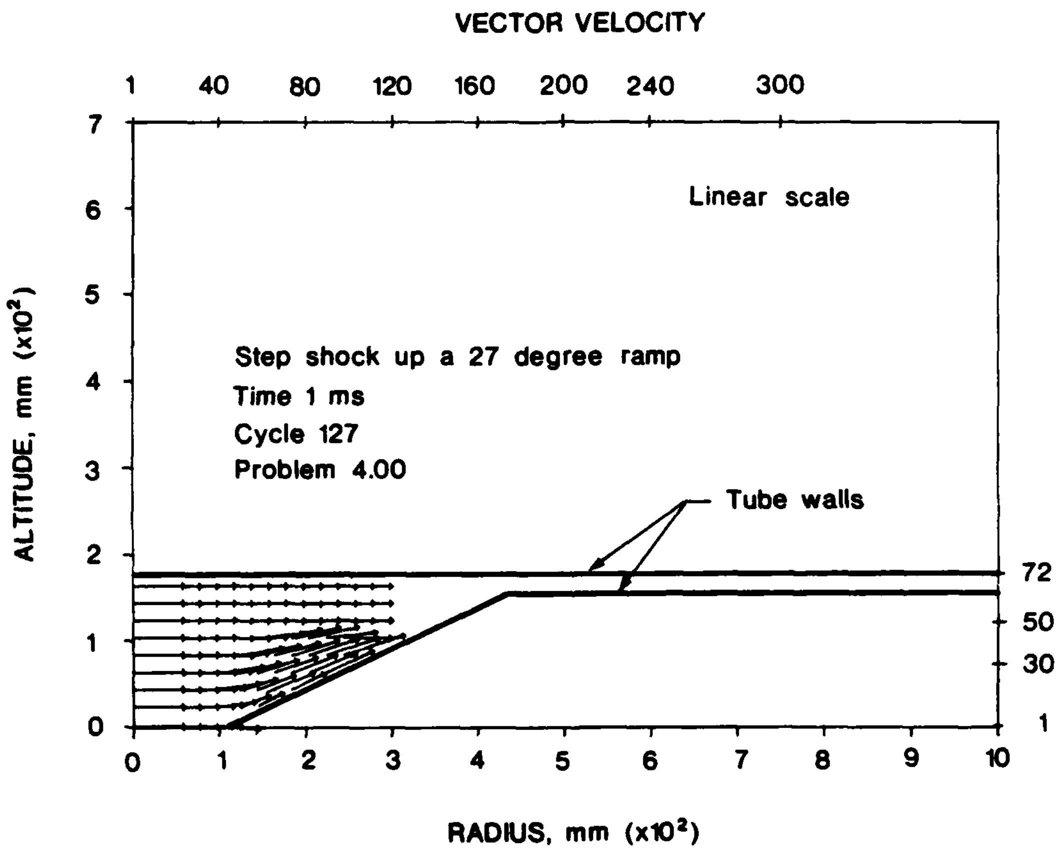


FIGURE 3(i) Vector Velocity vs Time

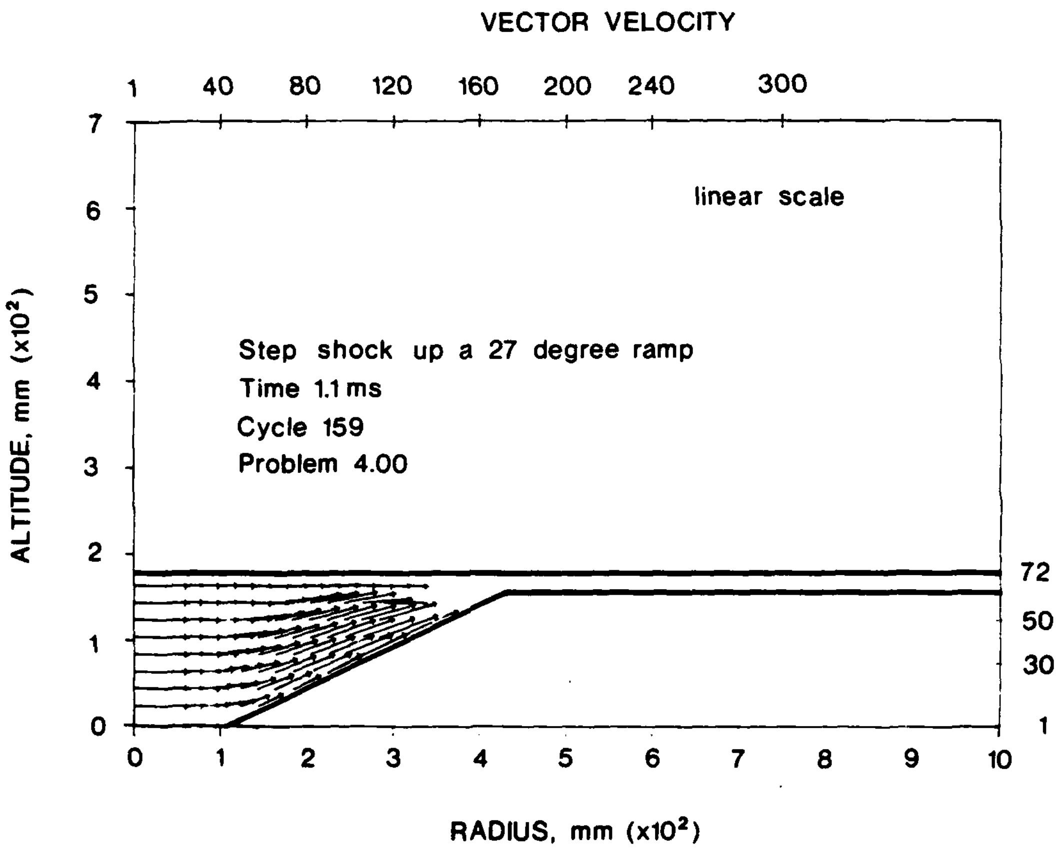
VECTOR VELOCITY
1
40
80
120
160
200
240
300
linear scale
Step shock up a 27 degree ramp
Time 1.1 ms
Cycle 159
Problem 4.00
ALTITUDE, mm (x10²)
72
50
30
1
0
1
2
3
4
5
6
7
8
9
10
RADIUS, mm (x10²)

FIGURE 3(ii)

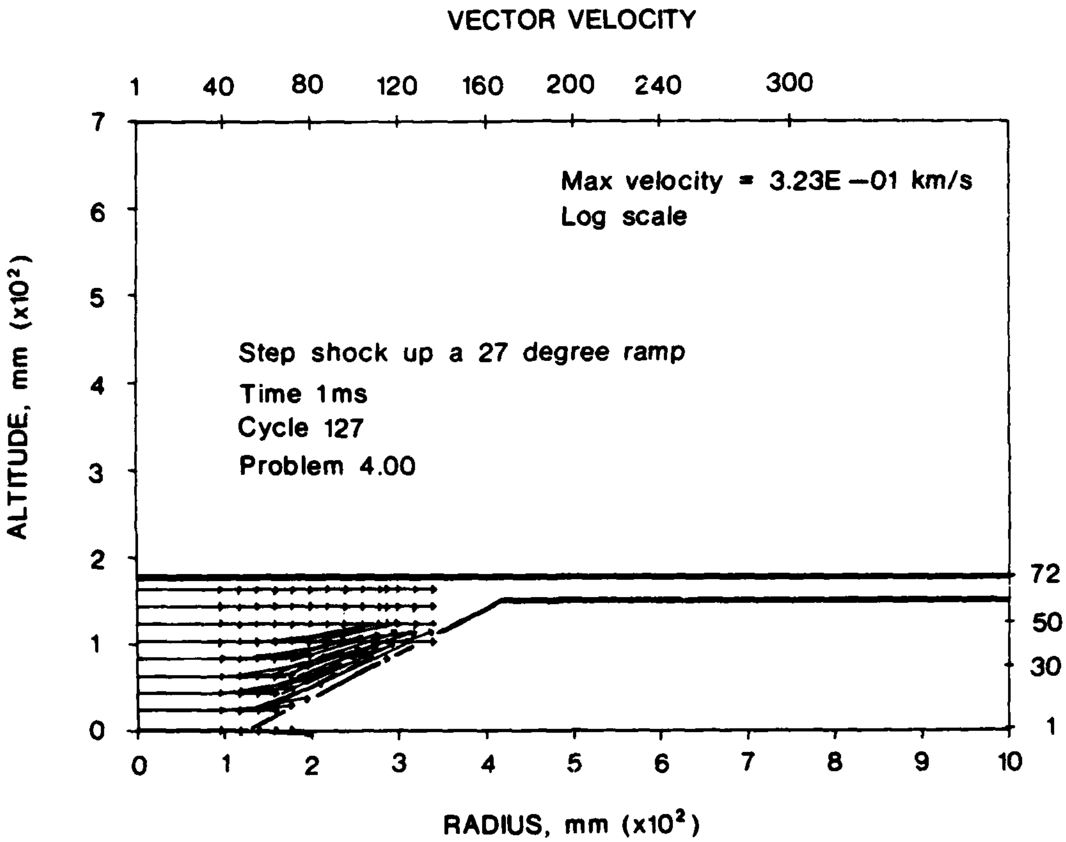
VECTOR VELOCITY
1
40
80
120
160
200
240
300
Max velocity = 3.23E –01 km/s
Log scale
Step shock up a 27 degree ramp
Time 1ms
Cycle 127
Problem 4.00
ALTITUDE, mm (x10²)
0
1
2
3
4
5
6
7
72
50
30
1
0
1
2
3
4
5
6
7
8
9
10
RADIUS, mm (x10²)

FIGURE 3(iii)

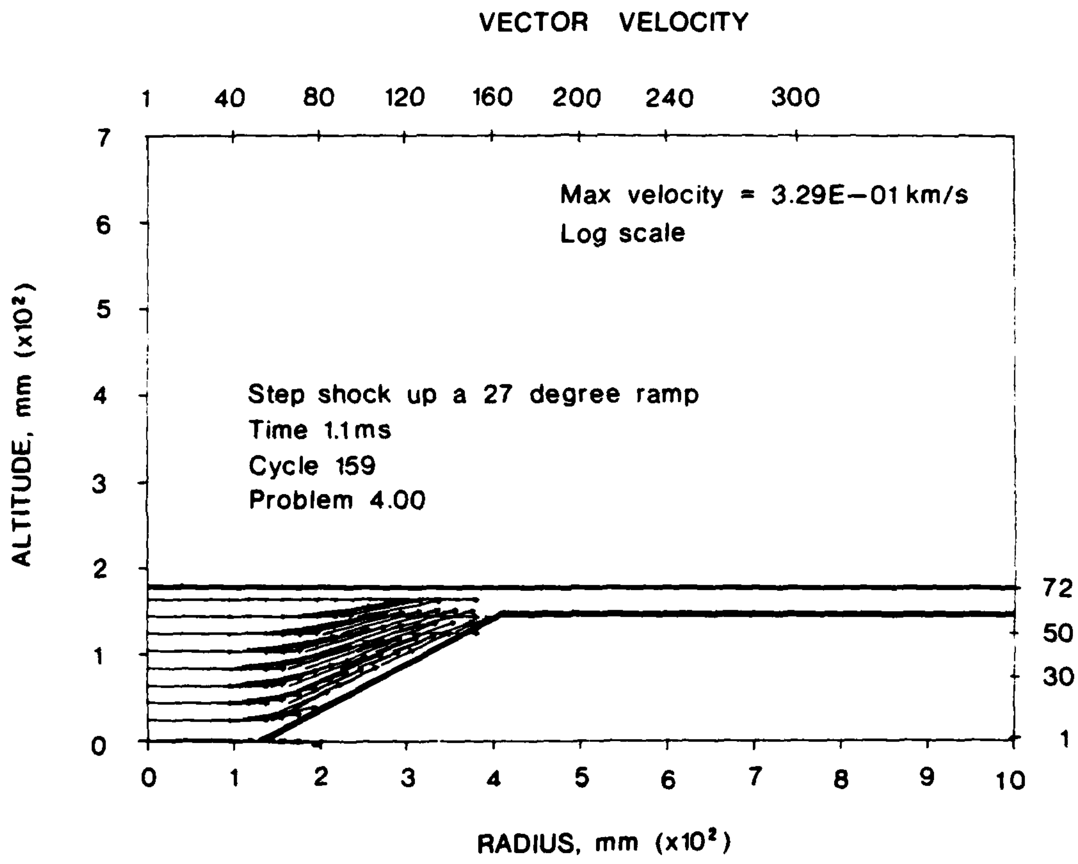
VECTOR VELOCITY
1 40 80 120 160 200 240 300
Max velocity = 3.29E−01 km/s
Log scale
Step shock up a 27 degree ramp
Time 1.1 ms
Cycle 159
Problem 4.00
ALTITUDE, mm (x10²)
0 1 2 3 4 5 6 7
72 50 30 1
0 1 2 3 4 5 6 7 8 9 10
RADIUS, mm (x10²)

FIGURE 3(iv)

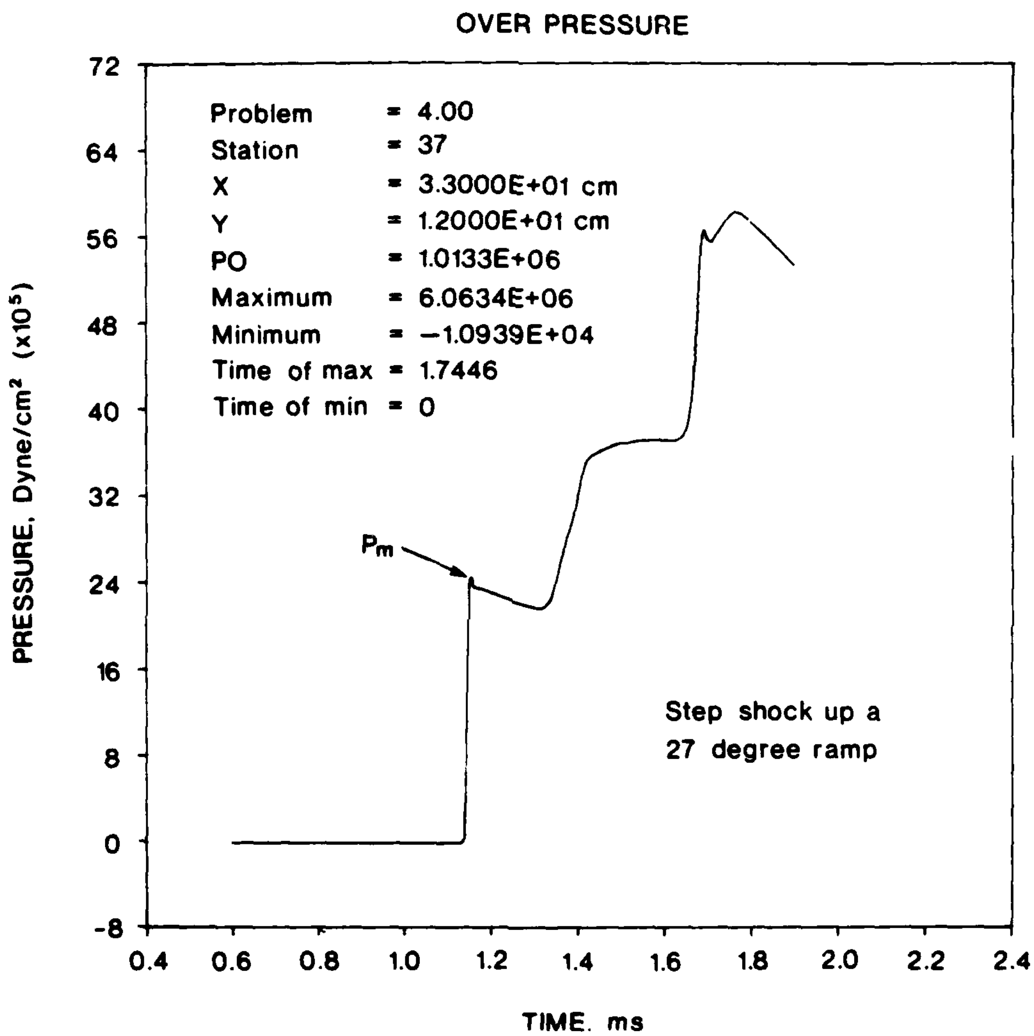


FIGURE 4(i) Overpressure variation at location A.

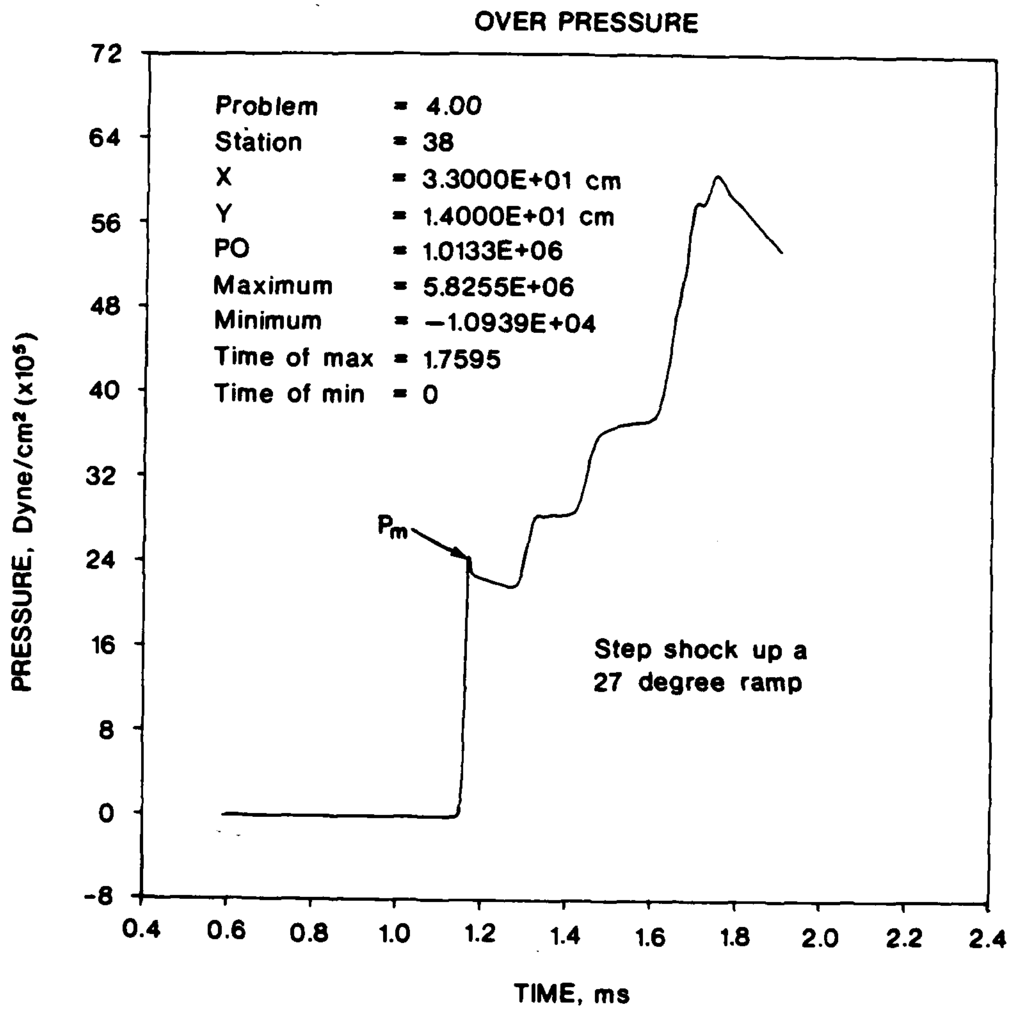


FIGURE 4(ii) Location B.

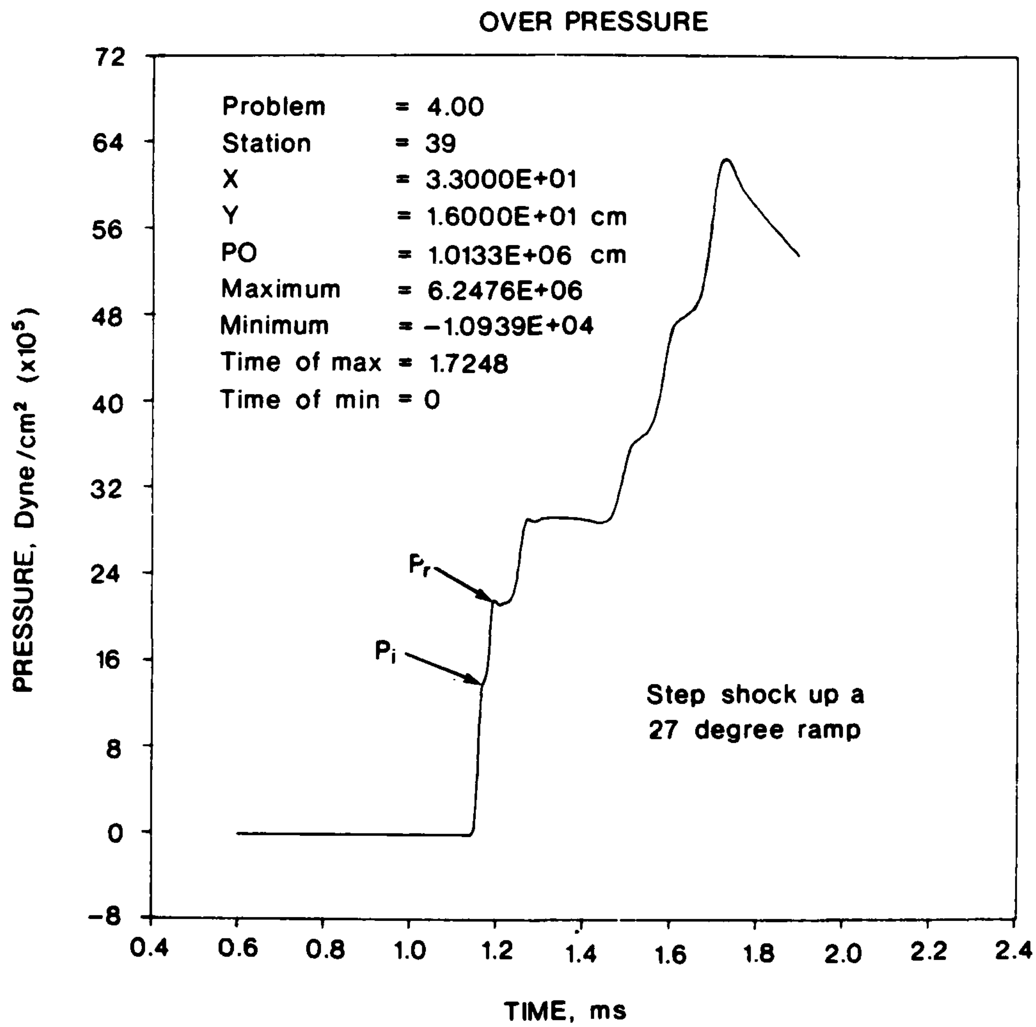


FIGURE 4(iii) Location C.

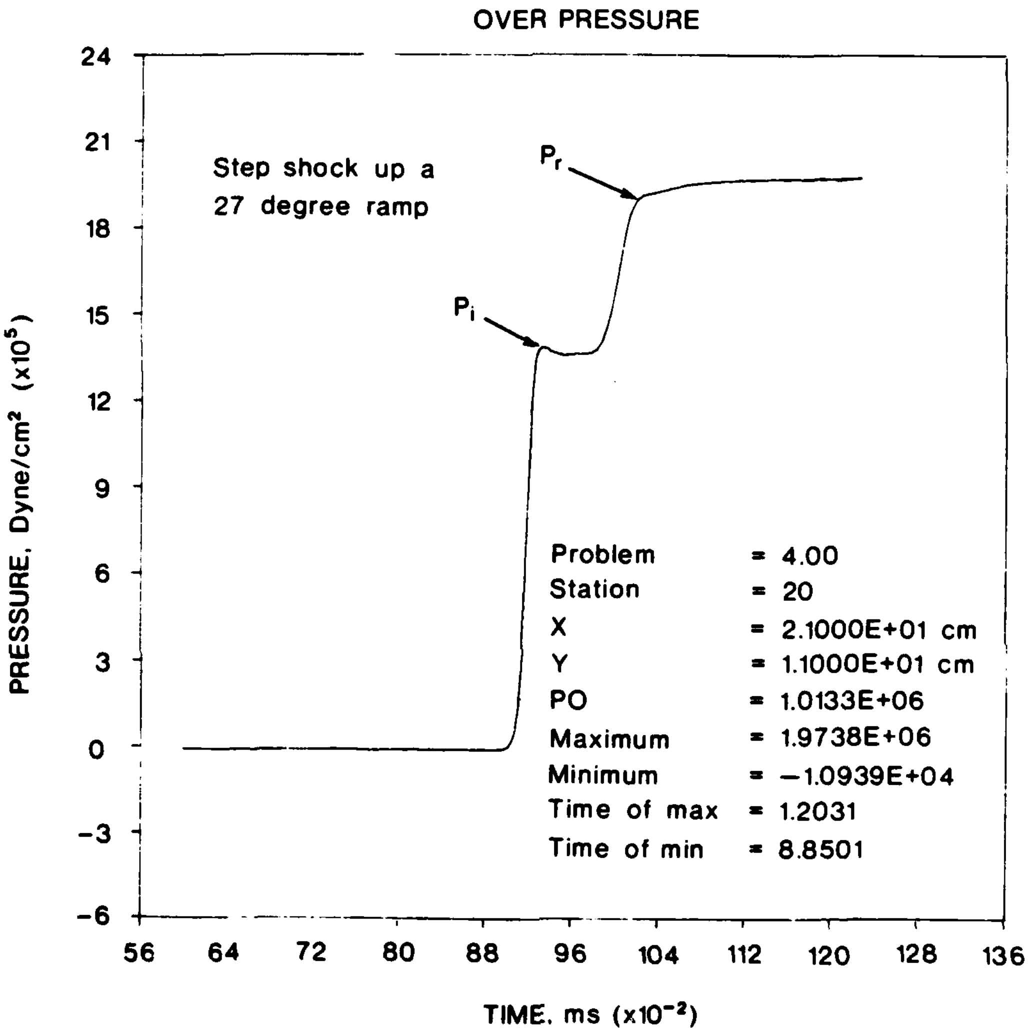


**FIGURE 4(iv)** Location D.

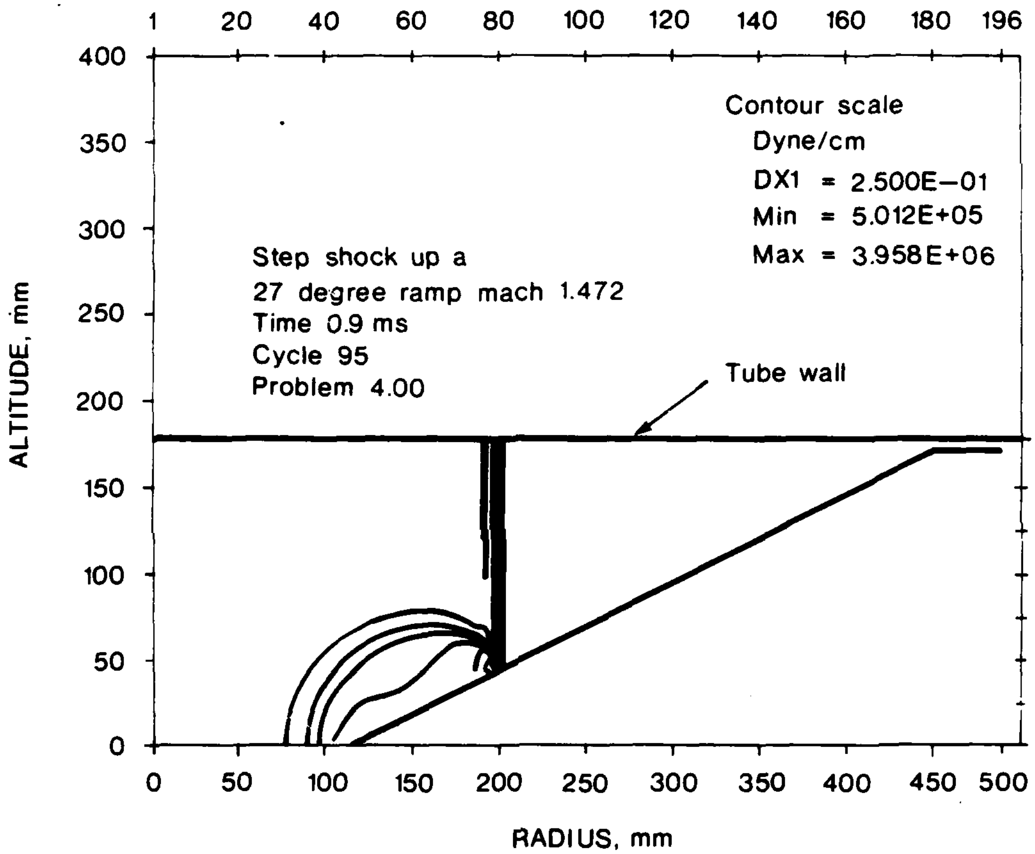


FIGURE 5(i) Pressure contours showing Mach Stem formation along the wedge.

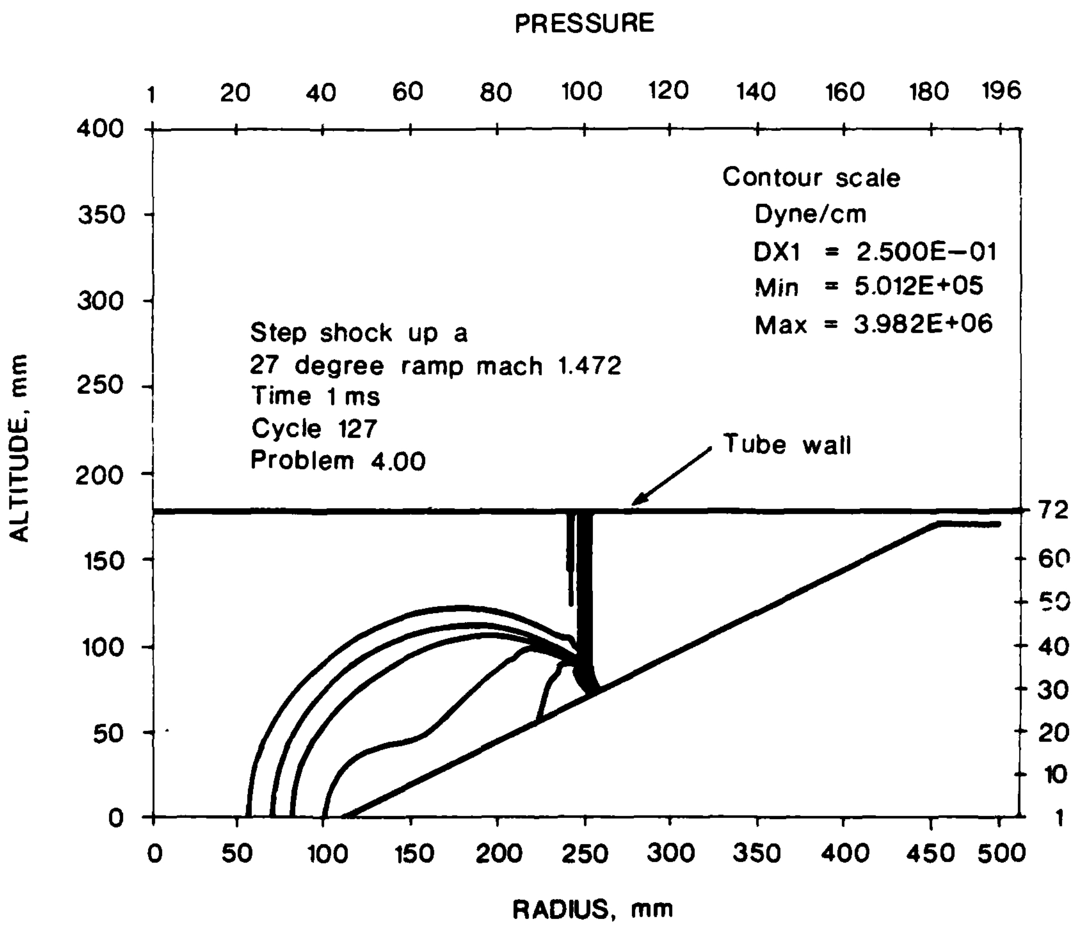
PRESSURE
1
20
40
60
80
100
120
140
160
180
196
400
350
300
250
200
150
100
50
0
Contour scale
Dyne/cm
DX1 = 2.500E−01
Min = 5.012E+05
Max = 3.982E+06
Step shock up a
27 degree ramp mach 1.472
Time 1 ms
Cycle 127
Problem 4.00
Tube wall
ALTITUDE, mm
72
60
50
40
30
20
10
1
0
50
100
150
200
250
300
350
400
450
500
RADIUS, mm

FIGURE 5(ii)

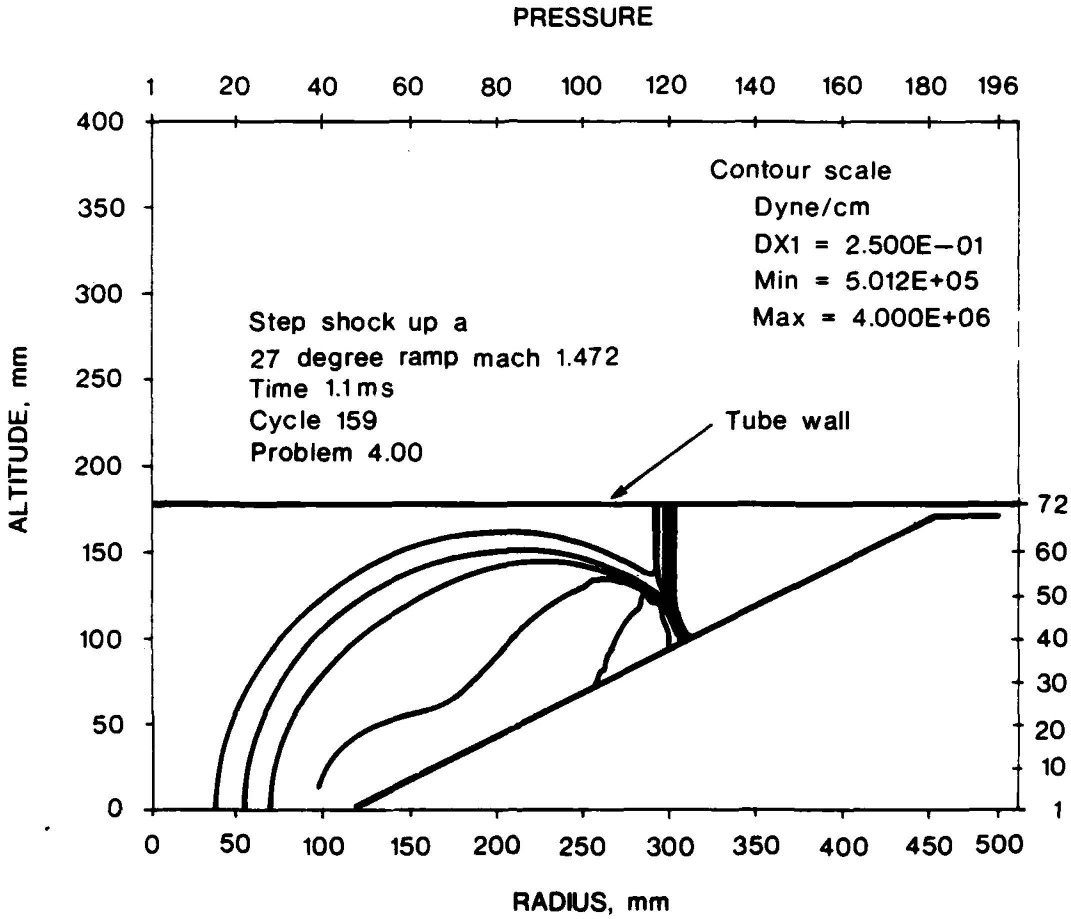
PRESSURE
1
20
40
60
80
100
120
140
160
180
196
400
350
300
250
200
150
100
50
0
ALTITUDE, mm
Contour scale
Dyne/cm
DX1 = 2.500E−01
Min = 5.012E+05
Max = 4.000E+06
Step shock up a
27 degree ramp mach 1.472
Time 1.1ms
Cycle 159
Problem 4.00
Tube wall
72
60
50
40
30
20
10
1
0
50
100
150
200
250
300
350
400
450
500
RADIUS, mm

FIGURE 5(iii)

TABLE 2

SELECTED PEAK OVERPRESSURE VALUES (Pa)

| Peak / Locations | $P_i$ | $P_r$ | $P_m$ |
|---|---|---|---|
| A | - | - | $2.44 \times 10^5$ |
| B | - | - | $2.45 \times 10^5$ |
| C | $2.14 \times 10^5$ | $1.34 \times 10^5$ | - |
| D | $1.97 \times 10^5$ | $1.39 \times 10^5$ | - |

## 4. THEORETICAL CONSIDERATIONS

While there seems little doubt that a Mach Stem and Triple Point has been formed some calculations undertaken during this work were used to monitor the computer output and verify this assumption.

The Mach number of the incident shock, $M_i$, is given by

$$M_i = \frac{u_i}{a} \tag{1}$$

$$= 1.472$$

where a is the sonic velocity ($3.403 \times 10^2$ m/s), and $u_i$ is the shock velocity.

The associated pressure P, particle velocity u, density ρ and specific internal energy E can be derived from [4].

$$P_1 = \frac{2\gamma M_i^2 - (\gamma-1)}{\gamma + 1} P_o$$

$$u_1 = \frac{2(M_i^2 - 1)a}{(\gamma + 1)M_i}$$

(2)

$$\frac{\rho_1}{\rho_o} = (\frac{P_1}{P_o})/(\frac{T_1}{T_o})$$

$$\frac{E_1}{E_o} = \frac{T_1}{T_o}$$

where $\gamma$ is the ratio of the specific heats and T is the absolute temperature given by:

$$\frac{T_1}{T_o} = \frac{P_1}{P_o} \left[\frac{(\gamma-1)\ (P_1/P_o) + (\gamma+1)}{(\gamma+1)\ (P_1/P_o) + (\gamma-1)}\right]$$

and the subscripts o and 1 refer to the standard states [2] specified in Diagram 1. Comparison of values calculated from (2) and those supplied to HULL are given in Table 3. In each case, agreement is satisfactory.

TABLE 3

VALUES OF PARAMETERS FOR SHOCKED AIR

| PARAMETERS | FROM HULL INPUT | FROM FORMULAE |
|---|---|---|
| Pressure (Pa) | $2.393 \times 10^5$ | $2.393 \times 10^5$ |
| Particle velocity (m/s) | $2.247 \times 10^2$ | $2.248 \times 10^2$ |
| Density ($kg/m^3$) | 2.222 | 2.222 |
| Specific Internal energy (J/kg) | $2.692 \times 10^5$ | $2.661 \times 10^5$ |

Now consider the situation where the shock wave has travelled some distance up the inclined ramp and a Mach Stem has been formed, as indicated in Fig. 6. Here $M_i$ is the incident shock Mach Number, $M_m$ is the Mach Stem Mach Number, $M_r$ is the reflected shock Mach Number, $\theta_w$ the ramp angle and $\chi$ the Triple Point trajectory angle.

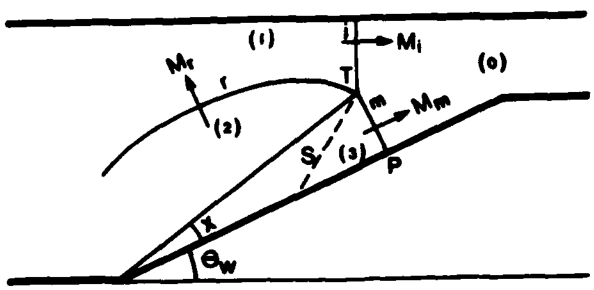


FIGURE 6. Motion of Shock Front Up Ramp.

Again using standard notation the angle of incidence of the shock wave with the ramp is given by:

$$90 - \theta_w$$

whence to a first approximation, the Mach number associated with the Mach Stem is given by:

$$M_m = \frac{M_i}{\sin(90 - \theta_w)} \tag{3}$$

$$= 1.652$$

From (2) an approximation to the pressure behind the Mach Stem is:

$$P_3 \sim \frac{2\gamma M_m^2 - (\gamma - 1)}{\gamma + 1} P_o$$

$$= 3.057 \times 10^5 \text{ Pa}$$

which leads to an overpressure value of $2.044 \times 10^5$ Pa. To a first order, this value agrees well with the overpressures at $P_m$ in Figs. 4(i) and (ii).

A more sophisticated approach involves the Whitham theory [5,6]. By using an auxiliary function A defined by

$$A = f(M)$$

$$\equiv \exp \left\{ -\left\{ \ln \frac{M^2 - 1}{M} + \frac{1}{\gamma} \ln \left(M^2 - \frac{\gamma - 1}{2\gamma}\right) + \ln \frac{1 - \mu}{1 + \mu} \right. \right.$$

$$+ \left(\frac{\gamma - 1}{2\gamma}\right)^{1/2} \ln \left[\mu + \left(\frac{\gamma - 1}{2\gamma}\right)^{1/2}\right] - \left(\frac{\gamma - 1}{2\gamma}\right)^{1/2} \ln \left[\mu - \left(\frac{\gamma - 1}{2\gamma}\right)^{1/2}\right]$$

$$+ \left(\frac{2}{\gamma(\gamma-1)}\right)^{1/2} \ln \left[\left(M^2 + \frac{2}{\gamma-1}\right)^{1/2} + \left(M^2 - \frac{\gamma-1}{2\gamma}\right)^{1/2}\right]$$

$$+ \left(\frac{1}{2(\gamma-1)}\right)^{1/2} \tan^{-1}\left\{\frac{[4\gamma - (\gamma-1)^2]\, M^2 - 4\,(\gamma-1)}{4\gamma^{1/2}(\gamma-1)\ [M^2 + (2/(\gamma-1))]^{1/2}\ [M^2 - (\gamma-1)/2\gamma]^{1/2}}\right\}\}\} \qquad (4)$$

$$\text{where} \quad \mu^2 \equiv \frac{(\gamma-1)\, M^2 + 2}{2\gamma\, M^2 - (\gamma-1)} \qquad (5)$$

values of the ramp angle and the triple point trajectory can be derived from

$$\tan \theta_w = \frac{(M_m^2 - M_i^2)^{1/2}\ (A_i^2 - A_m^2)^{1/2}}{A_m M_m + A_i M_i} \qquad (6)$$

$$\tan \chi = \frac{A_m}{A_i} \left\{\frac{1 - (M_i/M_m)^2}{1 - (A_m/A_i)^2}\right\}^{1/2} \qquad (7)$$

Using the initial estimate for $M_m$ of 1.652 and the known value of $M_i$, values of $A_m$ and $A_i$ can be calculated from (4) and (5), and hence $\theta_w$ and $\chi$ can be calculated from (6) and (7). In fact, if $\theta_w$ is assumed constant, a better value for $M_m$ can be obtained and the procedure repeated. On successful completion of this iterative process, (2) can be used to calculate the Mach Stem pressure and thus the overpressure. Results are shown in Table 4.

**TABLE 4**

**SHOCK PARAMETERS FROM WHITHAM THEORY**

| | | |
|---|---|---|
| Mach Number of Mach Stem | $M_m$ | 1.778 |
| Angle of Ramp | $\theta_w$ | 27° |
| Triple Point Trajectory | $\chi$ | 8° |
| Overpressure behind Mach Stem | P | $2.56 \times 10^5$ Pa |

The overpressure behind the Mach Stem as derived and shown in Table 4 is in very good agreement with that computed from locations A and B and shown in Table 2.

The Whitham theory can also be used to predict the Mach number $M_r$ of the wave as reflected at the ramp given by

$$M_r^2 = \frac{\gamma-1}{2\gamma} + \frac{((\gamma+1/2\gamma)\ [M_m^2 - (\gamma-1)/2\gamma]}{M_i^2 - (\gamma-1)/2\gamma}$$

$$= 1.421$$

or $$M_r = 1.192$$

The velocity of this reflected wave is not constant; its overpressure varies depending on both the path length and instantaneous velocity. A range for the expected overpressures is between that corresponding to the Mach number of 1.192 (hence a maximum overpressure of $2.56 \times 10^5$ Pa) and that of the incident shock of $1.38 \times 10^5$ Pa. Comparison with the HULL values for peak $P_r$ at C and D on Table 2 confirms this result.

Finally, the theoretical value for the Triple Point trajectory (as shown in Table 4) is in good agreement with the value of 8.2° as measured from Figures 5(i) - 5(iii).

## 5. CONCLUSION

The sophisticated computer code HULL can be used to simulate a shock front impinging on an inclined ramp. Many more complex investigations are planned both within a shock tube and in the study of blast phenomena from detonating explosive charges. The next phase in this work will incorporate the development of a User Manual for the Australian version of the code.

## 6. ACKNOWLEDGEMENTS

The assistance of Mr J.H. Keefer of the US Army Ballistic Research Laboratory, Aberdeen, Maryland in supplying the tape in a form compatible for the CSIRO Cyber 7600 is gratefully acknowledged.

The commissioning of such a large code as HULL on the Cyber 7600 required considerable effort from many people. Particular thanks are due to Mr J.J. Masinskas for his very helpful advice and insight in those early critical stages of development and to Dr R.E. Lottero, BRL, for his valuable comments during the preparation of this Report.

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6. Whitham, G.B. 1974. Linear and Non-Linear Waves. Wiley and Sons, N.Y.

# APPENDIX A

## Input Data for KEEL run

```
*EOS
KEEL
PROB 4.0
BBOUND=0
TBOUND=0
LBOUND=7
RBOUND=1
ATMOS=5
COLD=TRUE
DIMEN=2
EOS=2
GEOM=1
HEADER
    STEP SHOCK UP A 27 DEGREE RAMP
ISLAND=1
SHORE=1
IMAX=300
JMAX=72
T=0.0
PTSTOP=0.080
REZONE=0
NSTN=4
RELGAM=1.4003
RELRHO=1.225E-3
RELSIE=2.044E9
RELPO=1.01325E6
MESH
XO=0.0  NX=300  DX=0.25
YO=0.0  NY= 72  DY=0.25
GENERATE PACKAGE AIR
I=0.269152E10
U=0.224738E5
V=0.0
RHO=0.002222
RECTANGLE
X1=-3000  X2=5.0
Y1=-3000  Y2=3000
PACKAGE SHORE TRIANGLE
X1=11.00  Y1=0.0  X2=45.0  Y2=17.0  X3=45.0  Y3=0.0
PACKAGE ISLAND
RECTANGLE
X1=45.0  X2=75.0
Y1=0.0   Y2=17.0
STATIONS
XS=21.0  YS=11.0
XS=33.0  YS=12.0
XS=33.0  YS=14.0
XS=33.0  YS=16.0
*EOP
```

# APPENDIX B

## Input Data for HULL RUN

```
*EOS
HULL
PROB 4.0000
CYCLE=440
INPUT
T=6.0E-4
SHKTST=-9.982E-5
SHKAZM=0.0
SHKWVL=50087.7
SHKPVL=22473.8
SHKEBS=2.69152E9
SHKRHO=0.002222
MRELER=1.0E-6
REZONE=0
STABF=0.5
CSTOP=700
*EOP
```

# APPENDIX C

Input Data for PULL Run to Plot:

(A) Vector Velocity

```
*EOS
PULL
PROB 4.0
PLOTPKG=6
PLTXPG=7
PLTYPG=10
PLTFTR=5
VVECT
CTIME=0.001,0.0011,0.0012
*EOP
```

(B) Station Data

```
*EOS
PULL
PROB 4.0
PLOTPKG=6
PLTXPG-7
PLTYPG=10
STATION
PLTFTR=10
FSTA=19
LSTA=24
*EOP
```

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